23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

EXPERIMENTAL AND MODELLING STUDIES ON EXPLOSIVE REACTIVE ARMOUR INITIATION MECHANISMS.

P J Haskins[1], M D Cook[1], J P Curtis[1], J Stubberfield[1],
P Cheese[2] and P.R. Lee[3]

[1]QinetiQ, Fort Halstead, Sevenoaks, Kent, UK TN14 7BP
Tel: +44 1959-514006, Fax: +44 1959-516050, e-mail phaskins@qinetiq.com.
[2]Defence Ordnance Safety Group, Defence Procurement Agency, Bristol, BS34 8JH
[3]Peter Lee Consulting Co. Ltd., 8 Upton Quarry, Langton Green, Tunbridge Wells, Kent TN3 0HA

Will an Explosive Reactive Armour (ERA) fulfil its function through detonation of its explosive layer on being impacted by a projectile? This important question is one main driver for research into explosive response. Progress towards a flexible capability to answer it in diverse scenarios forms the subject of this paper. Specifically we report on a controlled set of experiments for calibration and then validation of QinetiQ’s models. Both the QinetiQ Cook Haskins Arrhenius Reaction Model (CHARM1), which is a burn model for hydrocodes, and an analytical semi-empirical model are then exercised. Brief descriptions of the models are provided and the experimental trials configuration described. Explosive sandwich configurations, typical of those that occur in ERAs, comprising steel front and back plates with SX2 and Primasheet 1000 fillings are investigated. Good agreement between the model predictions and experiment is demonstrated within the scope of the models.

INTRODUCTION

Will the explosive layer of an explosive reactive armour (ERA) detonate or not when it is hit by a projectile? The effectiveness of the ERA depends crucially on this question, because effective disruption of the incoming threat requires detonation to occur. The prevalence of ERA renders it imperative to have suitable modelling tools.

Several physical mechanisms govern ERA response. The mechanism known as deflagration to detonation transition (DDT) is believed to be the governing process for ERA configurations with a thicker front plate, when hit by a kinetic energy (KE) projectile. An ERA with a thinner front cover plate may react more violently to impact through the mechanism called shock to detonation transition (SDT). However, in both cases an appreciation of both the shock and the shear mechanisms is needed to gain a better understanding of the causes of detonation under typical KE penetrator impact conditions, likely to include obliquity.

The most flexible type of tool for the investigation of such questions is a hydrocode-based ignition and growth model, although there have been many worthy attempts to describe explosive response analytically [1-6]. The hydrocode allows the treatment of shock propagation and reflection, even in complex three-dimensional geometrical situations, provided the mesh is suitably selected. By contrast, the analytical models have largely been focussed on normal impacts and have a higher level of empiricism. They can nonetheless be useful in parametric or vulnerability studies where multiple shotlines are needed and the physical regime is within the scope of the model.

This paper reports some experiments and simulations which are focussed mainly on the further development of the QinetiQ hydrocode-based ignition and growth model, namely the Cook Haskins Arrhenius Reaction Model 1 (CHARM1) [7]. The predictive capability of the model is applied to problems associated with typical ERA in DYNA2D. We describe the use of both CHARM1 in the DYNA hydrocode and an analytical model for the Response of Confined Explosives (RECONEX), also developed by QinetiQ in conjunction with Lee [8-10], to make predictions.

Initially, the model validation process used some small scale experimental data which involved gun firing a steel flat-fronted fragment simulating projectile (FSP) weighing 27g at small scale targets. The experiments were conducted with the front plate barrier at an obliquity of zero degrees. The experiments were designed to determine the critical detonation velocity as a function of a steel front plate barrier thickness across a range of impact velocities. Additional highly instrumented experiments will also be reported and were used with the fragment attack results to validate the relevant parts of the CHARM1 model's Arrhenius reaction chemistry.

OVERVIEW OF CHARM1 IGNITION AND GROWTH MODEL

CHARM1 has been described previously [7]. It is a temperature dependent ignition and growth of reaction model for energetic materials that uses three-step Arrhenius chemistry, identical to that developed by McGuire and Tarver [11], to describe the chemical reaction from solid (or liquid or gaseous) energetic material to gaseous products with the associated release of energy. CHARM1 was developed primarily to describe energetic material response, principally shock-to-detonation transition. CHARM1 is essentially a multi-step thermal explosion model which can be used with or without mesocopic hot spot sub-models switched on. It provides the foundation to model the full range of responses observed in energetic materials from combustion through burn to violent reaction (BVR) to detonation. However, further development is required to meet this goal.

The basic CHARM1 functionality can be used to model homogeneous explosives. Heterogeneous explosives can be modelled be means of explicit discrete mesoscopic hot spot models (the most commonly used being based on adiabatic heating of gas upon pore collapse) that act with the underlying homogeneous model to reproduce heterogeneous features. The model thus has the unique capability to describe both homogeneous and heterogeneous behaviour, particularly features such as shock desensitisation, in a physically meaningful way in a single model. The CHARM1 model has been implemented in both Lagrange and Eulerian hydrocodes.

In the work reported here we have used the DYNA2D hydrocode [12] with the CHARM1 model implemented as a separate equation of state. Material data for the casing and projectile have been obtained from the open literature. The only parameters that need to be derived for the CHARM1 model are the hot spot parameters, which can be estimated from knowledge of the morphology and porosity of the material. The remaining parameters are standard physical constants such as specific heat capacity over a range of temperatures, thermal conductivity and reacted and unreacted Hugoniots. For the energetic material, this data is not always available. Furthermore, the constitutive properties that describe the mechanical behaviour of the material as it is deformed are not widely measured for explosives, although some data is available which can be used as an estimate. Under shock conditions, the behaviour can be described by an unreacted equation of state (EOS). This typically takes the form of a shock velocity – particle velocity relationship. These data are available for a wide range of materials in the Lawrence Livermore Explosives Handbook by Dobratz [13].

The product gases, formed once the explosive has reacted, are described by the Jones-Wilkins-Lee (JWL) EOS which describes the pressure – volume – energy behaviour of the detonation products of explosives particularly in applications involving metal acceleration. JWL parameters are usually fitted to cylinder expansion test data or can be calculated using a thermochemical equilibrium code such as Cheetah [14] by fitting to the calculated adiabatic expansion of the product gases. The Arrhenius parameters required for CHARM1 are obtained by fitting the McGuire-Tarver scheme within a heat flow code to One-Dimensional-Time-to-eXplosion (ODTX) data [13]. The parameters so obtained can be used directly in CHARM1 since it has been demonstrated that the same chemical kinetic scheme can be used to model both Cook-Off and shock.

OVERVIEW OF RECONEX ANALYTICAL MODEL

The analytical modelling utilises the RECONEX code [8-10], which comprises a one-dimensional shock propagation model of the series of interactions between the projectile and the cover plate, of the cover plate and the explosive, etc. The Rankine-Hugoniot relations, expressing continuity of mass and momentum before and after an interaction, are the mathematical basis of the model. These relations are supplemented by a Murnaghan EOS for each of the materials [9], with simple treatments of obliquity and attenuation effects. The attenuation of pressure in the explosive is modelled by an exponential decay. Self consistent shocked states are calculated by the Rankine-Hugoniot equations.

The critical impact velocity is taken to be the velocity needed for the explosive to gain internal energy at a certain rate. The internal energy rate is given by the specific internal energy of the explosive in its shocked state multiplied by the mass rate at which the material becomes shocked. The mass rate is proportional to the cross-sectional area of the shock, which, in the first instance, is equal to that of the impacting projectile. The code can calculate the impact velocity required for a given energy rate at the front or rear of the explosive. Curtis *et al.* [10] give details of previous validations of the code.

FRAGMENT IMPACT STUDIES

A fragment impact trial, designed to establish the SDT thresholds for the two explosive materials, was carried out. A schematic diagram of the experimental set up is shown at Figure 1. The thresholds were obtained by positioning a front plate barrier of various thicknesses in front of the explosive charge. The explosive charge was made using a minimum of ten laminates of the respective material. The FSPs were typically flat nosed at 13.15mm diameter by 25.4mm in length and with a weight of 27g. The projectiles were housed in acetal co-polymer sabots and fired from a 30mm Rarden Cannon. The explosive target was placed on a wooden block and taped to a metal support beam that was attached to a sabot stripping plate assembly. The FSPs were fired at the target through a 50mm diameter hole in the sabot stripping plate. Firings were observed with two Photonics Phantom 7 digital video cameras at framing rates of 50,000 and 100,000fps. One camera was set up to determine projectile velocities, reveal projectile orientation at the moment of impact and provide visual confirmation of the degree of reaction of the target charge. The other camera was used to observe close-up the reaction of the target. This can range from no reaction, through burning and deflagration, to detonation. Two banks of seven flash bulbs were used to back-illuminate the charge.

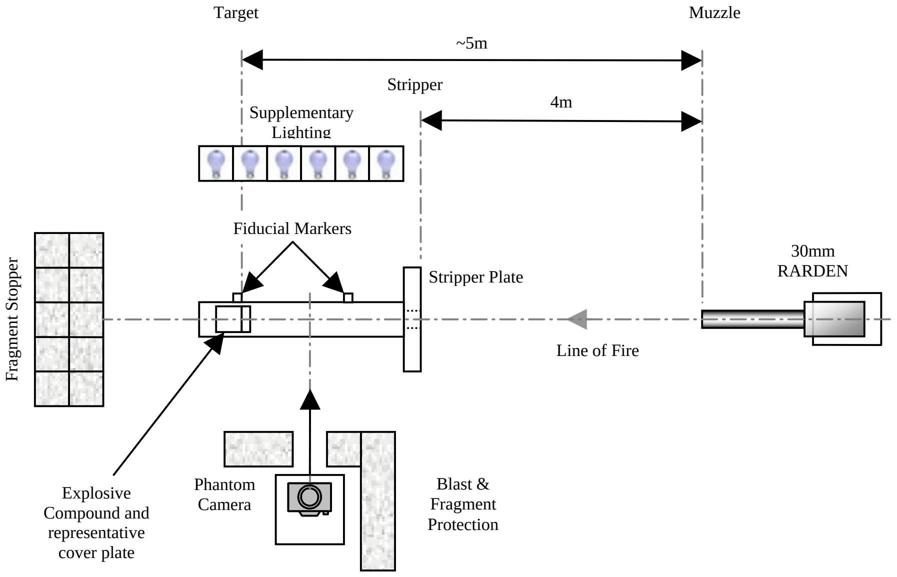

Figure 1. Schematic diagram of the experimental set up.

Figure 2 shows three frames from the Phantom camera video record and gives a typical example of what can be observed from the experiments. The first frame shows the incoming projectile on the left hand side just after the first upright fiducial marker. The second frame shows the projectile just before the second upright fiducial and the third frame shows the SDT reaction with the target. The fiducial markers are used to determine the projectile’s impact velocity. Figure 3 shows the results obtained for Primasheet 1000 as a plot of the fragment impact velocity against steel cover plate thicknesses up to nine millimetres. Both the lowest velocity detonations and the highest velocity non-detonations are given. A similar plot for SX2 is given in figure 4. For both explosives, it can be seen that there is a smooth progression in the velocity required to induce an SDT condition as the barrier thickness increases.

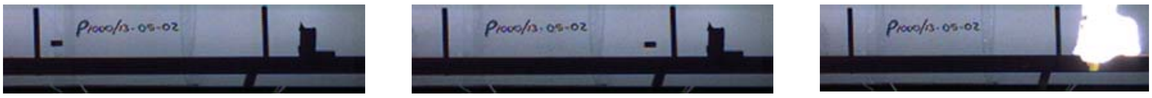

Figure 2. Three individual frames from the Phantom camera
video records showing a typical SDT reaction

It is clear that Primasheet 1000 is more sensitive to this form of initiation than SX2 is. Note also that the first four points for Primasheet 1000 are essentially flat, unlike those for the SX2. In order to achieve the results it was necessary to fire a considerable number of rounds to obtain acceptable boundaries between the lowest velocity detonation and the highest velocity non-detonation.

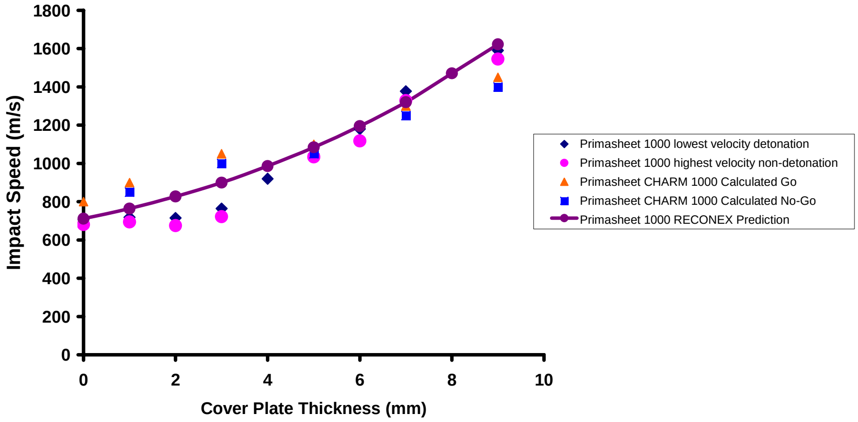

Figure 3. Data points giving the threshold fragment velocity for detonation of Primasheet 1000. Also shown are predicted values for Go and No-Go by CHARM1 and the RECONEX prediction of the threshold velocity.

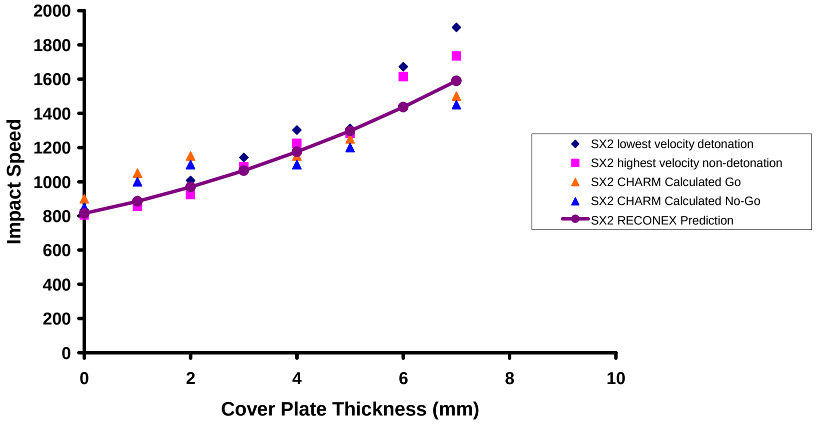

Figure 4. Data points giving the threshold fragment velocity for detonation of SX2. CHARM1 and RECONEX predictions are also shown.

COMPARISONS OF HYDROCODE AND ANALYTICAL PREDICTIONS WITH EXPERIMENT

The calculated threshold velocities for Primasheet 1000 and SX2 are plotted in figures 3 and 4 respectively. The unreacted equation of state parameters were obtained from plate impact experiments. The reacted equation of state data was obtained from the ideal detonation code, Cheetah (Version 2). All the kinetics parameters were obtained from modelling the ODTX experiments. Only the hot spot parameters were adjusted to obtain the best fit to the fragment impact data. It is recognised that this suggests that other hot spot mechanisms such as friction and shear may be more relevant to these materials. This will be investigated in future work. The pore collapse model has nonetheless provided a useful baseline.

Comparisons of the analytical predictions by RECONEX [10] with experiment have been made. The predictions for Primasheet were made using the critical energy rate value of 50 J/µs for Detasheet, as used for the Weickert data [9,15]. The exponential attenuation function was chosen by fitting the data at 9 mm. The same attenuation function was used to make the qualitative SX2 explosive predictions with the higher critical energy rate of 125 J/µs. Here the results were fitted at zero thickness cover-plate, but are then predicted fairly well for higher values of cover plate thickness.

CONCLUSIONS

We have described QinetiQ fragment attack experiments to determine the threshold for detonation and have demonstrated that the QinetiQ CHARM1 model implemented in the DYNA hydrocode, once parameterised for SX2 and Primasheet 1000, can make good predictions of the threshold fragment impact velocity for the detonation. The analytical model RECONEX has also been shown to make fair predictions under the circumstances of normal impact. It remains to perform further validation experiments both with the same explosives and others.

ACKNOWLEDGEMENTS

This work was carried out as part of the Weapons and Platform Effectors Domain of the MoD Research Programme, with further support provided by MoD DPA DOSG. J. Curtis acknowledges the support of a Royal Society Industrial Fellowship and an Honorary Senior Research Fellowship at University College London.

REFERENCES

[1] Held, M., “Initiation Phenomena of Uncovered or Covered High Explosive Charges by Shaped Charge or Projectiles”, *Proceedings of the 3rd International Autumn Seminar on Propellants, Explosives, and Pyrotechnics*, pp. 273-289, Oct. 5-9, 1999.

[2] Walker, F.G. and Wasley, R.J., “Critical Energy for Shock Initiation of Heterogeneous Explosives”, *Explosivestoffe* 17, pp. 9-13, 1969.

[3] James, H.R., “The Response of Bare Explosives to Attack by Cylindrical and Spherical Projectiles”, *AWRE Report No.* O 6/86, Aug., 1986.

[4] James, H.R., Haskins, P.J., and Cook, M.D., “Prompt Shock Initiation of Cased Explosives by Projectile Impact”, *Propellants, Explosives, Pyrotechnics*, 21, pp. 251-257, 1996.

[5] Lee, P.R., “Critical Power Density: A Universal Quantitative Initiation Criterion”, *10th International Symposium on Ballistics, San Diego, USA*, pp. 1-6, Oct., 1987.

[6] James, H.R., “An Extension to the Critical Energy Criterion Used to Predict Shock Initiation Thresholds”, *Propellants, Explosives, Pyrotechnics*, 21, pp. 8-13, 1996.

[7] M. D. Cook, P. J. Haskins and C. Stennett, “Development and Implementation of an Ignition and Growth Model for Homogeneous and Heterogeneous Explosives”, *Proceedings of the Eleventh Symposium (International) on Detonation, Snowmass, Colorado*, 30 August – 4 September 1998, p587.

[8] Lee P. R., Curtis J. P., Mills J. T., and Lynch N. J., “A Critical Energy Rate Model for the Prediction of Shock-Induced Detonation of Explosives”, *Proceedings of the 14th American Physical Society Topical Conference on Shock Compression of Condensed Matter, Baltimore, Maryland, USA*, July 31-August 5, 2005.

[9] Curtis J. P., Mills J. T., Lynch N. J., Cornish R., and Lee P. R., “An Analytical Model for High Velocity Impact on Confined Explosive Configurations” *Proceedings of the 9th Hypervelocity Impact Symposium, Lake Tahoe, USA*, 9-14 October, 2005.

[10] J.P. Curtis, M.D. Cook, P.J. Haskins, J.T. Mills, P.R.Lee, A. Wood, K.G. Cowan, N.J. Lynch, J. Stubberfield, R.I. Briggs, P.R. Ottley, J. Mann, and H. Flower, “Experimental Validation of an Analytical Model for Prediction of Shock to Detonation Transition Resulting From High Velocity Impacts”, *13th. International Detonation Symposium, Norfolk, VA, USA*, July 23-28, 2006.

[11] R. McGuire, C. M. Tarver, “Chemical Decomposition Models for the Thermal Decomposition of Confined HMX, RDX, TATB and TNT Explosives”, *Proc 7th Symposium (International) on Detonation, Annapolis, MD, USA*, NSWC MP-82-334, 1982.

[12] R. G. Whirley and B. E. Engelmann, DYNA2D, “A nonlinear, explicit, two-dimensionsl finite element code for solid mechanics”, *LLNL*, UCRL-MA-110630.

[13] D. M. Dobratz The Lawrence Livermore National Laboratory (LLNL) Explosives Handbook Properties of Chemical Explosives and Explosive Simulants, , UCRL-52997, March 1981.

[14] E. Catalano and R. McGuire, E. L. Lee, E. Wrenn, D. Ornellas, and J. Walton, *Sixth Symposium on Detonation, Office of Naval Research, ACR-221, Coranado, CA*, 1976, p214.

[15] C. A. Weickert, “Jet initiation of explosive/metal sandwiches.” *Proceedings of the 10th International Symposium on . Ballistics, San Diego, California, USA*, 27-29 October, 1987.